CHAPTER 22

FLUID CONDUCTORS

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22.1 INTRODUCTION

Fluid conductors are the means by which the entire fluid system is connected. It is therefore very important to assure the reliability of the various connections in the system. Many times in evaluating a fluid system for reliability, the major components such as pumps, valves and actuators are analyzed while overlooking the fluid-carrying link between the components. These fluid conductors are usually very reliable from a design standpoint but their reliability can be very sensitive to the operating environment.

Conductors of a fluid power system are basically of three types: pipe, tubing and hose. A pipe is a rigid conductor not intended to be bent or shaped into a configuration. Tubing is a semi-rigid fluid conductor which is usually bent into a desired shape for the particular application. Hose is a flexible fluid conductor which can be adapted to components that move during operation.

There are many factors to consider when evaluating the reliability of a fluid conductor system. For example, newer designs are combining tubing and hoses as hybrid assemblies. These assemblies provide the strength and heat dissipation characteristics of metal tubing with the flexibility and vibration dampening characteristics of hose.

The failure modes presented in this Chapter should be considered for the particular application of the fluid conductor because the failure rate of a fluid conductor is probably more sensitive to the operating environment of the system in which it is installed than to the design parameters. Each application must be evaluated individually because of the many installation, usage and maintenance variables that affect the failure rate.

22.2 PIPE

Most failures of fluid conductor systems occur at or within the interconnection points such as fittings and flanges. Reliability of the system therefore depends on the proper selection of interconnecting components that are compatible with each other and the operating environment. Considerations include strength, ductility, hardness, and corrosion resistance. A pipe that can deflect more than 2% in diameter without cracking is considered a flexible pipe, one that cannot deflect to this degree is deemed rigid.

Piping components are designed for an internal pressure to compensate for the most severe condition of fluid pressure and temperature expected in normal operation. In addition to normal fluid operating pressures, potential back pressures, pressure surges, temperature fluctuations and performance variations of pumps, valves and other components must also be considered in the evaluation of fluid conductor systems. These conditions are met using the greatest required pipe thickness and the highest flange rating. The system must also be evaluated for the maximum external differential pressure conditions.

Older fluid conductor systems are comprised of threaded pipe and many hydraulic systems had NPT ports. This type of connection is the least reliable for high-pressure fluids as the thread itself provides a leak path. Because pipe threads are deformed when tightened, any subsequent movement, either loosening or tightening, increases the potential for leaks. Threaded connections have more recently been replaced by more reliable soft seal connections.

System temperatures need to be evaluated when estimating reliability. A single over-temperature event of sufficient magnitude can permanently damage all the seals in an entire high-pressure fluid system resulting in numerous leaks. Also, prolonged operation at above-normal temperatures can produce the same results.

The life of a pipe system depends not only on the material, but the installation and the surrounding environment. Typical pipe system materials include high density polyethylene (HDPE), cross linked polyethylene (PEX), acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), stainless steel, carbon steel, copper and ductile iron. One material does not exhibit a significant difference in lifespan from another. When properly designed and installed, pipe systems of any of these materials can be sufficiently durable to exhibit extremely low failure rates. Plastic pipe can exhibit some long term failure modes due to chemical attack, deterioration from ultraviolet rays, change in dimension (creep) and environmental stress cracking. Failure data indicates no difference in the failure rate between pressure and gravity flow systems assuming proper pipe material selection and layout and proper tightness of pressure system connections to avoid leaks.

22.2.1 Failure Modes of Pipe Assembly

As mentioned previously, most failures of a pipe assembly occur at or within the interconnection points. The life of a pipe system depends not only on the material, but the installation and the surrounding environment. The following failure modes need to be considered when evaluating a pipe assembly for reliability:

- Burst failure caused by internal pressure
- Buckling caused by external pressure
- Bending failure
- Stress related failure from applied loads
- Excessive leakage at the interconnection points

A common failure mode in pipe systems is caused by a sudden reduction in liquid flow in a pipe. When a valve is abruptly closed, dynamic energy is converted to elastic energy creating a pressure wave called water hammer that can cause pipe failure.

Table 22-1 provides a summary of potential failure modes of a pipe assembly.

22.2.2 Reliability Prediction of Pipe Assembly

The failure modes presented above should be considered for the particular application of the fluid conductor. The failure rate of a fluid conductor is extremely sensitive to the operating environment of the system in which it is installed as compared to the design of the pipe. Each application must be evaluated individually because of the many installation, usage and maintenance variables that affect the failure rate.

The internal pressure in piping normally produces stresses in the pipe wall because the pressure forces are offset by pipe wall tension. The longitudinal stress from pressure is calculated by:

$$S_L = \frac{P_D\, D}{4t} \qquad \textbf{(22-1)}$$

where: S_L = longitudinal stress, psi
P_D = internal design pressure, psi

D = outside pipe diameter, in
t = pipe wall thickness, in

Table 22-1. Typical Failure Modes of Pipe Assemblies

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
Damaged connector	- corrosion - improper torque on fitting - gasket failure	Gradual increase in system leakage
Burst failure	- rapidly applied load - pressure transients	Catastrophic pipe assembly failure
Buckling failure	- insufficient piping supports	Immediate leakage above system requirements
Bending failure	- bend radius less than allowable	Immediate leakage above system requirements
Crack in rigid pipe	- external stress	System leakage
Leakage	- chemical incompatibility with fluid - chemical attack/improper thread sealant - ultraviolet deterioration	Gradual increase in system leakage
Fatigue failure	- water hammer from upstream component	System fluid leakage

The burst pressure of the pipe is determined as follows:

$$P = \frac{2\,t\,S}{D} \qquad \textbf{(22-2)}$$

where: P = burst pressure, psi
t = pipe wall thickness, in
S = tensile strength of pipe material, psi

D = outside pipe diameter, in

And the working pressure is equal to:

$$WP = \frac{P}{sf} \tag{22-3}$$

where: WP = working pressure
P = burst pressure
sf = safety factor (normally equal to approximately 3.0)

Since the failure rate of a piping assembly usually depends primarily on the connection joints, the basic failure rate of a piping assembly can be estimated at 0.47 failures/million operating hours per connection and the failure rate of the pipe assembly can be estimated with the following equation:

$$\lambda_P = \lambda_{P,B} \bullet C_E \tag{22-4}$$

where: λ_P = failure rate of pipe assembly, failures per million hours
$\lambda_{P,B}$ = base failure rate of pipe assembly, 0.47 failures/million hours
C_E = environmental factor, see Table 22-2

Table 22-2. Pipe Assembly Environmental Factor, C_E

Operating Environment	**Multiplying Factor, C_E**
Normal duty, non-flex pipe, ambient conditions, no vibration or shock	1.0
Heavy duty, flexible pipe under random pulsations	1.2
Severe duty, vibration and shock environment	1.4

See Chapter 3 of this Handbook to determine the failure rate of any seals being used in the pipe connectors.

22.3 TUBING

Components on many types of hydraulic equipment are connected by rigid tubing. Because it is rigid, tubing can transmit vibration from one component to another throughout the equipment. Therefore, many hydraulic designs utilize bent tubes and hoses providing the weight and bend advantages of bent tube with the flexibility and vibration dampening characteristics of hose.

Although tubing is a better heat dissipater than hose, in some applications the use of hose can actually result in less heat buildup because of improved laminar flow through the more gradual bends created between hose connections.

All metal-to-metal connections, such as compression and flared type, are sensitive to excessive torque. Thus, the failure rate of line connections is dependent on assembly methods and will significantly affect the infant failure region of the failure rate bathtub curve.

When the conductor assembly is used to provide actuator movement, it will be subject to vibration changing the torque on plumbing connections and causing metal fatigue. Reliability is thus affected by the routing and supporting of the fluid conductor assembly. Tube bending and fabrication require proper training and experience to acquire reliable connections. Misalignment causes strain on the tubing, which can lead to leakage or line failure once in service. Improper deburring and flaring can eventually lead to stress cracks after the lines have been installed.

22.3.1 Failure Modes of Tubing Assembly

Plastic tubing will exhibit different failure modes than that for metal tubing. One common failure mode is caused by the change of properties of the plastic over time and/or temperature. The strength and stiffness of many common plastics change dramatically over a relatively small change in temperature. Some plastics such as PVC can become brittle and will shatter when exposed to lower temperatures. The stiffness of many plastics changes when exposed to heat. Likewise, the amount of load or stress that some plastics can withstand will change over time (creep). Plastics can also fail when combining stress and chemicals (environmental stress cracking)

Leakage is the most common failure mode in fluid systems. Connections that incorporate an elastomeric seal such as BSPP and SAE-4 bolt flange offer the highest seal reliability. NPT is the least reliable type of connector for high pressure hydraulic systems because the thread itself provides a leak path. The threads are deformed when tightened and as a result, any subsequent loosening or tightening of the connection increases the potential for leaks.

A common cause of leakage from 37 degree flare joints is incorrect torque. Insufficient torque results in inadequate seat contact, while excessive torque can result in damage to the tube and connector through cold working.

Table 22-3 provides a summary of potential failure modes for tubing assemblies.

Table 22-3. Typical Failure Modes of Tubing Conductor Assemblies

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
Stress cracks	- excessive strain from misalignment - improper deburring and flaring	System leakage
Metal fatigue	- vibration	System leakage
Compressed air line leak	- line misalignment - vibration - excessive torque loading on compression fittings	Reduced compressor life
Damaged connector	- improper torque on fitting - external impact	System leakage
Tubing burst	- pressure transients - suddenly applied load	Immediate tubing assembly failure
Fluid leakage	- chemical incompatibility with fluid - Improper thread sealant	Gradual increase in system leakage
Tube buckling failure	- tubing support failure	Immediate leakage above system requirements

22.3.2 Reliability Prediction of Tubing Assembly

The equations for determining the burst and working pressures of a tubing assembly are the same as those derived in Section 22.2.2.

Since the failure rate of a tubing assembly usually depends primarily on the connection joints, the basic failure rate of a tubing assembly can be estimated at 1.33 failures/million operating hours per connection and the failure rate of the tubing assembly can be estimated with the following equation:

$$\lambda_T = \lambda_{T,B} \bullet C_E \tag{22-5}$$

where: λ_T = Failure rate of tube assembly, failures per million hours

$\lambda_{T,B}$ = Base failure rate of tube assembly, 1.33 failures/million hours

C_E = Environmental factor, see Table 22-4

See Chapter 3 of this Handbook to determine the failure rate of any seals being used in the tubing connections.

Table 22-4. Tubing Assembly Environmental Factor, C_E

Operating Environment	Multiplying Factor, C_E
Normal duty, ambient conditions, no vibration or shock	1.0
Heavy duty, random fluid pulsations	1.2
Severe duty, vibration and shock environment	1.4

22.4 HOSE

A hose assembly is comprised of three basic elements including the inner tube to convey the fluid, reinforcement to withstand the fluid pressure, and outer cover to protect the hose from abrasion and other environmental conditions. The failure rate of a hose assembly depends on its size, temperature, application, media, and pressure. However, even knowing all the operating parameters of a system, it is still difficult to predict the expected service life of a hose. Sometimes the best method of obtaining a predicted service life is reliance on an adequate maintenance program that includes fluid cleanliness and visual inspections for abrasion, heat damage, etc.

- Pressure – Pressure spikes that exceed the maximum rated working pressure can cause damage and early failure in a hose assembly, the pressure impulses causing the hose to expand and contract.

- Temperature – A single over-temperature event of sufficient magnitude or prolonged operation at above –normal temperature can permanently damage the seals in the hose assembly resulting in leakage. At higher temperatures plasticizers tend to leach out of elastomers faster the rate dependent on the temperature and duration. Excessively low temperatures can cause the hose to harden, take on a permanent set, and initiate hose cracking. Proximity to other components producing high temperatures can create shortened hose life.

- Application – An individual hose assembly is designed for a specific range of pressures, flows and temperatures and deviating from these design parameters in actual usage will obviously shorten the design life. Excessive flow velocity, for example, will damage the inner tube, especially at hose bends, and cause premature failure. Secondary failures can also be created in other system components caused by the increased temperature. Improper hose length can also cause failures from hose stretching in a hose assembly that is too short or excessive bending in a hose that is too long for the application. In general, mobile applications face harsher conditions than non-mobile permanent installations due to abrasion.

- Media – A fluid incompatible with a hose will shorten the design life of the hose. Consideration must be given to the chemical composition of the environment surrounding the fluid conductor assembly as well as the media being conducted including abrasive particles and corrosive properties when estimating the failure rate.

22.4.1 Failure Modes of Hose Assembly

Hose assemblies have a finite life, the main factor contributing to failure being service conditions. The following factors will affect the service life of metal hose:

- Pitting corrosion
- High fluid velocity combined with chemical abrasives
- Stress corrosion
- Vibration
- Torsion fatigue
- Tight radius bending and constant motion

Operating pressure – The maximum operating pressure within the hose should not exceed the recommended working pressure as specified by the manufacturer. Burst pressure should not be used as the operating pressure. Exposing the hose to pressures higher than the working pressure or exposing the hose to a surge pressure above the working pressure of the hose will shorten hose life.

Operating temperatures – High heat conditions may have an adverse affect on hose life due to the degradation of the rubber and the affect on fitting retention. Continuous use of the hose at or above the maximum allowable operating temperature will cause deterioration of the tube, cover and reinforcement thus reducing hose life. Fluid and ambient temperatures, both static and transient must not exceed the limitations of the hose.

External forces – Flexing the hose to less than its minimum bend radius, twisting or kinking the hose will reduce hose life. Evaluating a hose for reliability must therefore include an examination of fittings and adapters designed to prevent the impact of external forces. Excessive abrasion can damage the hose cover, accelerating hose failure.

Fluid and environmental compatibility – The expected life of a hose assembly depends on the chemical resistance of the tube, cover, 0-ring fitting and other hose components and compatibility with the fluid being used and the environment. Ultraviolet light, ozone, salt water and various chemicals can shorten hose life

Hose configuration – The size of the hose assembly components must be adequate to keep pressure losses to a minimum and avoid damage to the hose due to heat generation or excessive turbulence.

Table 22-5 provides a summary of failure modes for hose assemblies.

Table 22-5. Typical Failure Modes of Hose Assemblies

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
Metal hose fatigue failure	- high flow velocity - flexing of corrugations	- continual increase in size of crack until complete fracture
Excessive shear stress in metal hose	- twisting the hose during installation	- circumferential cracks
Irregular cracks in metal hose	- vibration	-eventual failure - leakage
Inner tube deterioration	- elevated temperature	- eventual hose failure - contaminants entering system
Excessive fluid temperature	- high fluid temperature caused by excessive flow velocity	- premature hose failure
Fractured hose	- excessively small bend radius - hose bend immediately behind the coupling	- reduced ability to withstand internal pressure
Hose leakage	- continuous exposure to high temperature - chemical deterioration	- loss of hose flexibility
Inner tube failure	- inadequate compatibility with fluid	- eventual hose failure

22.4.2 <u>Reliability Prediction of Hose Assembly</u>

The failure rate of hoses is very hard to estimate because of the varied operating conditions. Studies by fluid power part manufacturers indicate that the three most common causes of hydraulic hose failure are abuse, misapplication and improper assembly. Hydraulic hose manufacturers for example estimate that 80% of hose failures are attributable to external physical damage through pulling, kinking, crushing, or abrasion of the hose. Abrasion caused by hoses rubbing against each other or surrounding surfaces is a very common type of hose damage.

Hoses used on diesel engines historically have higher failure rates than those used on gasoline engines. Chemical deterioration causes hose failure and temperature accelerates chemical reaction. Diesel engines run hotter than gasoline engines.

22.4.2.1 Metallic Hoses

There are several factors associated with flexing that affect the service life of corrugated metal hose. Service life may be affected by factors external to the metal hose assembly such as the chemical composition of the environment surrounding the hose assembly as well as the media being transferred.

Turbulent flow of abrasive chemical media over the alloy surface of the hose may cause accelerated corrosion or erosion-corrosion. Liquids or gases that have suspended solid particles will wear or remove the oxide protective film of the hose and leave the alloy exposed and more susceptible to corrosion.

Fatigue is another failure mode to be considered. The flexing of the corrugations during hose operation can cause a failure of a progressive nature. Stress generated by flexure, pulsation, torsion, vibration and flow induced vibration are some other causes for fatigue failure. Applications where the flow of a liquid or gas is above manufacturer specifications and a liner is not incorporated into the hose assembly can result in premature fatigue failure. The high flow velocity causes the corrugations to vibrate at a high frequency and, if the vibration is near the natural frequency of the hose, failure can occur very quickly.

22.4.2.2 Non-metallic Hoses

The most common causes of a non-metallic hose assembly failure include:

- flexing the hose to less than the specified minimum bend radius
- twisting, pulling, kinking, crushing, or abraiding the hose
- operating the fluid system above maximum or below minimum temperature
- exposing the hose to surges in pressure above the maximum operating pressure

- intermixing hose, fittings and other parts that are not compatible

All hoses are rated with a maximum working temperature. Exposure to continuous high temperatures can lead to the hose losing its flexibility. Exceeding these temperatures can reduce hose life by as much as 80%. When hoses are exposed to high external and internal temperatures simultaneously, there will be a significant reduction in hose service life.

Bending a hydraulic hose in more than one plane results in the twisting of its wire reinforcement. A twist of five degrees can reduce the service life of a high-pressure hydraulic hose by as much as 70% and a seven degree twist can result in a 90% reduction in service life. Multi-plane bending is usually the result of inadequate clamping where the hose is subjected to mechanical motion.

Operating conditions have a direct effect on the service life of a hose assembly. Temperature extremes can accelerate the aging of the hose's rubber tube and cover. Frequent and extreme pressure fluctuations will accelerate hose material fatigue.

$$\lambda_H = \lambda_{H,B} \bullet C_E \bullet C_T \qquad \textbf{(22-6)}$$

where:

λ_H = Failure rate of hose assembly, failures per million hours

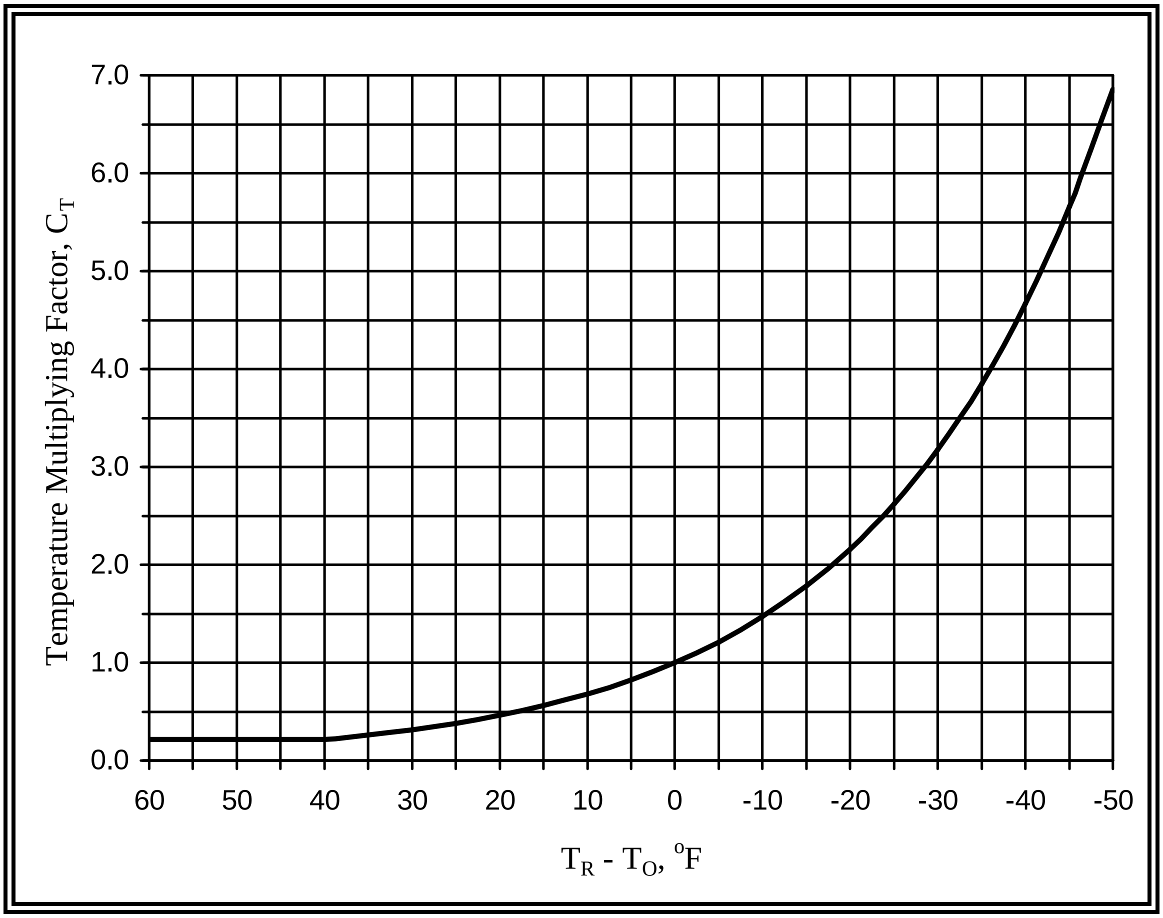
$\lambda_{T,B}$ = Base failure rate of hose assembly, 1.85 failures/million hours

C_E = Environmental factor, see Table 22-6

C_T = Temperature factor, see Figure 22.1

Table 22-6. Hose Assembly Multiplying Factor, C_E

Environment	Environmental Factor, C_E
Normal duty, ambient conditions, no vibration or shock	1.0
Heavy duty, random fluid pulsations	1.2
Severe duty, vibration and shock environment	1.5



$$C_T = \frac{1}{2^t}$$

Where: $t = \frac{(T_R - T_O)}{18}$ for $(T_R - T_O) \leq 40$ °F

and: $C_T = 0.21$ for $(T_R - T_O) > 40$ °F

T_R = Rated Temperature of Hose, °F

T_O = Operating Temperature of Hose, °F

Figure 22.1 Temperature Multiplying Factor, C_T

22.5 REFERENCES

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92. PST =>Solutions! ,Volume 3, October 1996